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COMPARATIVE ANALYSIS OF SHELTER PANEL DESIGNS WITH
CONSIDERATION GIVEN TO FIELD UTILIZATION

R. Kenneth Dalton

Army Materiel Command
Texarcana, Texas

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R. Kenneth Dalton
Maintenance Effectiveness Graduate Engineering Program
USAMC Intern Training Center
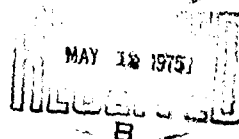Red River Army Depot
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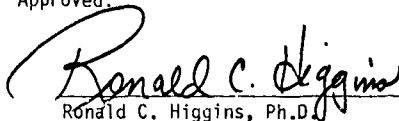
FOREWORD

The research discussed in this report was accomplished as part of
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The ideas, concepts, and results herein presented are those of the
author and do not reflect acceptance or approval by the Department of
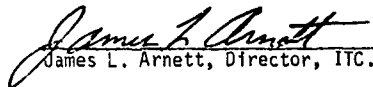the Army.

This report has been reviewed and is approved for release. For
further information on this project contact Dr. Ronald C. Higgins,
Intern Training Center, Red River Army Depot, Texarkana, Texas 75501.

Approved:

Ronald C. Higgins, Ph.D.
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For the Commander

James L. Arnett, Director, ITC.

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ABSTRACT

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ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Keeping in step with the concept of a modern Army, Army personnel are now extending a great deal of effort towards the development of a cost effective family of protective shelters. The cessation of the draft has forced the Army to re-evaluate its position and begin showing more concern for the selection and use of shelters. With the reduced amount of manpower, more work must be accomplished and in less time in order to maintain the same level of operational readiness. Not only are troops required to do more work, but they must also be a much more mobile unit.

In the past, the Army operated from basic tent type structures. During the initial states of conflict, tents were used as protective devices. These shelters were used primarily as temporary coverings. As time progressed, permanent shelters replaced the tents (1)*. Although they were sufficient for the World War II time frame, these shelters seriously hamper the mobility requirement that now confronts the Army. This requirement has necessitated the use of strong, lightweight, composite materials in some building applications. These materials are usually bonded honeycomb core panels or bonded foam core panels.

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* Numbers in parentheses refer to numbered references in the List of References.

Some work in the area of composite materials has dealt with the performance of advanced aircraft components. The testing methods developed in these various programs can be used in an analysis of sandwich panel configurations. Life expectancy, residual strength, and reliability of bonded structures are all areas of concern to be dealt within this study.

Within the Department of Defense there are a number of shelter panel designs in use. The type of panels to be used should be selected on the basis of the system requirements. Maximum strength, minimum weight, and the range of environments are a few of the constraints that shelters must satisfy in order to be effective.

The immediate concern in the selection of panel designs are the problems of bond integrity and panel construction. There are many different processes in this area and it would be virtually impossible to cover each completely. The best approach for the reader is to gain a general insight into bond formation and panel construction.

Bond integrity is the principal cause of panel failures. When the bond is weak, the chances of delaminations within the core increase greatly. A direct result of delaminations is the entrapment of water within the core. The presence of moisture causes increased shelter weight and a reduction in the maximum strength capacity of the shelter. Many times these failures are serious since the shelters must be rendered useless in order to affect repairs.

Shelter panels are constructed using three different techniques. The first of these, pour-in-place (or foam-in-place), is the oldest and most versatile method for the application of rigid urethane foam.

Freshly mixed liquid formulations are charged directly into the cavity between the inner and outer skins. This mixture foams to approximately thirty or forty times its ori, .al volume. When the foam mixture is poured into the cavity the mixture itself is extremely tacky; consequently, anything coming in contact with this liquid becomes securely bonded to it. Foaming in this manner allows all corners and cracks to be filled evenly forming a long seamless core. This offers a distinct advantage in that seams, joints, and lines, which tend to fail at low temperatures are eliminated.

The disadvantages of this method stem from poor quality control and manufacturing processes. For example, if the foam is not properly mixed, incomplete chemical reactions result in the formation of free isocynate, which is a salt of isomeric cyconic acid (HCNO). In the presence of moisture, the free isocynate forms urides or refoams causing local swelling. Urides are gummy substances which cause delaminations of the skin.

The second method used is called slabbing, or simply slab foam. This process is accomplished using a method called laminating. An adhesive is applied to the inner and outer skins as well as the foam slab; after completion of this process, the combination is placed in a vacuum press or passed through rollers to form a panel. Again poor quality control standards and poor manufacturing processes can adversely affect panels formed in this manner.

Panels are constructed using rolled sheets and extruded hat sections built to some preassigned tolerances. If the assembly

process is not closely watched, an accumulation of tolerance errors may occur. This could result in the eventual panel failure.

Adhesives are normally applied using a spray gun technique and the layer varies in thickness throughout both sides of the panel. A build-up of tolerance errors develops allowing air to be trapped between panel skins and hat sections. These pockets of air prevent bonding in the surrounding areas and also provide areas for the entrapment of moisture which leads to further delamination and corrosion (2).

The use of paper honeycomb core is the third method of panel fabrication. Paper honeycomb core panels are assembled in a manner very similar to .lab foam. Honeycomb offers the advantages of a very high strength-to-weight ratio, impact resistance, and high rigidity per unit weight. ⊤ restrictions on honeycomb are quite different than those on slab foam. One of the main disadvantages, and perhaps the most serious, is the water mig. .ion characteristics of paper honeycomb. The presence of water in honeycomb core panels is especially detrimental to this panel configuration.

Water directly affects the rigidity characteristic of honeycomb walls, and the adhesive between the core and skin. Given enough time, the honeycomb core walls and the bond will completely deteriorate. Harmful amounts of water can rest within the core because of the cell structure honeycomb exhibits. Unlike honeycomb core panels, slab-foam panels do not suffer from the problem of moisture within the core. Since slab-foam cores are not made up of cell structures, but are comparatively solid cores, water within the core is not predominant.

The current paper honeycomb design emphasizes the inhibition of water migration within the core.

Even before these problems are encountered, the designer must first decide on the adhesive and its method of application. The time between the application of the adhesive and the time of pressurization is critical. Adhesives tend to set rapidly and good bonds cannot be formed if only partial curing takes place in the joints prior to pressure application.

The type of adhesive selected has the greatest design impact on paper honeycomb construction. Honeycomb core panels depend upon the adhesive bond between skin and core for most of their structural strength. Delamination in this construction is serious. Foamed-in-place and slab-foamed panels differ in that they depend on the bond strength between the skin and the hat-section for their structural integrity. It is this area, as shown in Figure 1, that is subjected to the major loadings and not the skin core interface (2).
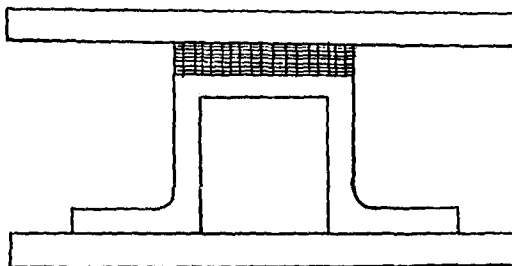
Figure 1:   Internal Substructure of Foam Panels.

Due to th   ˈɪ structure of honeycomb, stronger adhesives are also required. ᵤₑₛ than half the total area of the skin is actually bonded to the core, whereas with foam panels the entire skin is bonded to the core. Since a smaller area of the honeycomb face sheet is bonded, the need for a stronger adhesive is evident.

There are many more areas that can be discussed concerning the selection of an adhesive. In fact, this is an area of research by itself. The above mentioned constraints are the essential considerations that must be realized from the beginning of the selection process.

The Army is now concentrating a great deal of design effort towards the development of a mobile family of rigid wall shelters. The use of paper honeycomb core panels or foam core panels characterize rigid wall shelters. A requirement such as portability further restricts the type design to be utilized. With this constraint the designer must consider to a greater extent such areas as structural strength, weight, equipping mounting ease, electromagnetic and radio frequency interference (EMI/RFI), and cost. Since a family of shelters is the ultimate objective, these shelters should satisfy all of these restrictions and, as the name family implies, be of the same basic construction. This study examines each of these panel designs. The shelter is considered as a unit and evaluated on the basis of structural strength, weight, equipment mounting ease, EMI/RFI, and cost.

A survey of existing test methods and their results is presented in Chapter II. Current Army needs and projected panel requirements are

discussed in Chapter III. Chapter IV presents the comparison of different shelter panel designs according to material characteristics. This analysis would aid the design engineer by reducing the number of configurations that are feasible for a given use. The results of the analysis are given in Chapter V. In order to get an idea of the current thought on composite materials, an examination of cu ent testing methods and their results is necessary.

CHAPTER II

RELIABILITY ANALYSIS OF COMPOSITE MATERIALS AND
REVIEW OF TESTING METHODS FOR ADHESIVE STRENGTH CHARACTERISTICS

The concept of composite materials and their uses is not new. For
many years aircraft designers realized the weight savings and increased
strength properties these materials offered when compared to conven-
tional metal structures. Even considering this, the concepts
governing the utilization of composite materials in the design process
are in the infantile stage of progression.

As the state of the art of composites evolved, their first appli-
cations involved the substitution of these materials for metal
structures. Design engineers, in an effort to save time, adopted the
safety factor philosophy of metallic structures for composite materials.
It has since been proposed to use a structural reliability methodology
to assure the life of a composite material (8). Using this method the
design engineer must realize three things:

1) Reliability is concerned with the entire structure - - not
    just single components.

2) Reliability depends on emperical data and assumes an
    equivalency between actual and service environments.

3) Probabilistic models are used to relate distributions of
    residual strength and panel lifetime to the initial static
    strength distribution.

8

This approach to reliability enables the engineer to compare distributions of strength and lifetime to achieve the desired probability of survival. Once determined, these probabilities of required lifetime and residual strength can then be used to determine the reliability. The product of the probabilities of required lifetime and residual strength is the reliability of the element. System reliability goals are then specified for the system through a combination of elemental reliabilities. If the elements within the system were all identical and independent, the system reliability would be the product of the element reliabilities. This design procedure can be summarized by the flow chart depicted in Figure 2. In order to utilize this procedure, information must be furnished by the procuring agency covering: 1) Exceedance data in the form of maximum stress and shear levels along with design loads, 2) Desired design lifetime, and 3) Desired reliability goals. This information is obtainable through a series of tests covering the composite materials static strength behavior as well as its lifetime behavior. Maximum stress-strain values are found using the stress-strain diagrams available for the particular composite material in question. Since composite materials act very much like brittle materials, it is essential to account for the stress concentration factors (8). This additional requirement is necessary inasmuch as composite materials lack a yield point. The absence of a yield point is shown graphically in Figure 3.
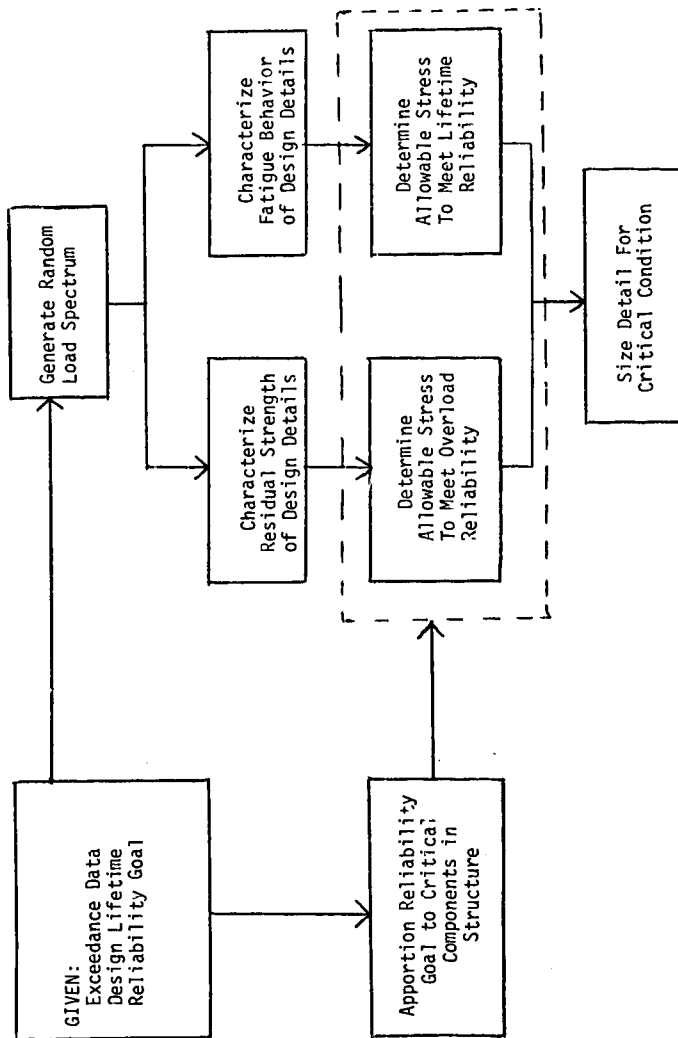
Figure 2 Block Diagram Representation of Reliability Based Design (8).

Stress

Composite
material

A

B

fracture

yield
point

metal

fracture
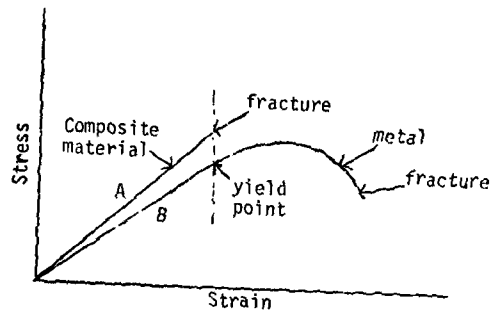
Strain

Figure 3: Stress-Strain Curves of Composite Materials and Metals.

Without this consideration, it is doubtful that the desired level of
static strength capacity is achievable (8).

Determination of lifetime behavior, on the other hand, is made by
subjecting the specimen to a series of cyclic load tests for fixed
periods of time (8). The material is then statically tested to deter-
mine the residual strength and specimen lifetime (resistance to
fatigue) for a given number of cycles (8). Curves of this form, as
shown in Figure 4, are often referred to as S-N plots. These plots
are especially useful in determining upper limits on the strength
characteristics for a given probability (8). This particular point can
be explained by referring to Figure 5 which is nothing more than an
expanded view of Figure 4. Examination of Figure 5 shows that for a
reliability of .999 the maximum number of load cycles the specimen
can withstand is approximately 10^6 cycles. Whereas, if the reliability
requirement is lessened, the maximum number of load cycles, or the
specimen lifetime, is increased (8).

Figure 4: Common form of S-N Plots.
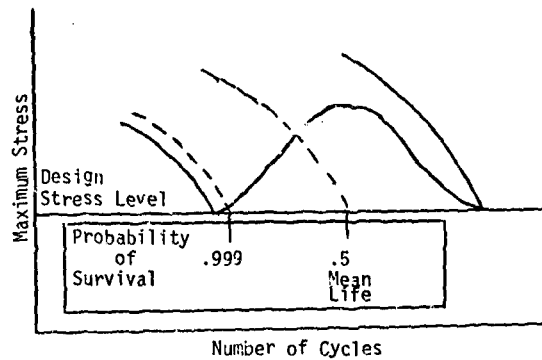
Figure 5: Expanded View of S-N Plots in Figure 4.
As the reliability increases the number
that survive decreases.

Dr. J. C. Halpin of the Air Force Materials Laboratory has suggested a probabilistic fatigue, or lifetime behavior, model (8). This model is based on the fact that composite material lifetime characteristics are dominated by a single fracture mechanism - damage growth in adhesive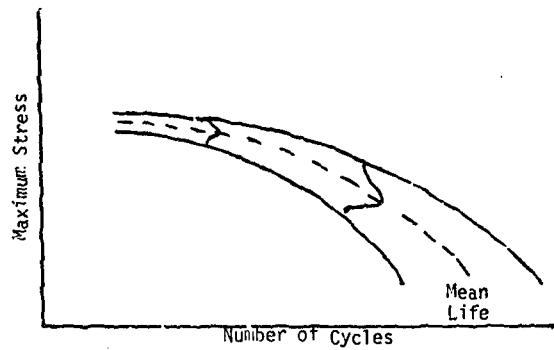. For brittle materials, damage growth rate can be characterized in terms of residual strength capacity. The distributions of life and residual strength are related by a growth equation to the initial static strength distribution. With this model, shown in Figure 6, the two essential parameters that are needed are the spectrum peak load (F_{max}) and the residual strength capacity desired (F_r or F_{ref}) (8). The ideal case for this model is when $F_{max} = F_r$ or F_{ref}. This model was found to describe residual strength and lifetime results within the limits of preliminary design applications (8).

Before much of what has been discovered on reliability can be used, it is imperative that data be obtained on the materials to be evaluated. The behavior of composite materials is a function of the adhesive characteristics (1).

Failure of adhesively bonded materials often originates at the interface between the face sheet and the core. These malfunctions can occur for a number of reasons: 1) process breakdowns; 2) low adhesive forces at the interface due to improper surface preparation; or 3) low cohesive strength of the bonding material resulting in improper curing and in moisture absorption (1). All of these would have a detrimental affect on panel integrity. Thus far one of the few

RESIDUAL STRENGTH DISTRIBUTION

$$P(F_R(t) > F_{mix}) = \exp - \{ F_R^{2(r-1)} + A_4(r-1) A_1^{2r} (t-t_0)) / \beta_0^{2(r-1)} \}^{\alpha_0/(2(r-1))}$$

Where β_0 = Static Scale Parameter

r = Flaw Growth Rate Exponent

$A_1 = F_{max}/F_{ref}$ F_{max} = Spectrum Peak Load

$F_{ref} = F_{max}$ Where Data Exists

A_4 is Material and History Dependent Constant

t = time

t_0 = Initial Time

LIFETIME DISTRIBUTION

$$P(T>t) = P\{F_R(t) > F_{max}\} = \exp-(t/\beta_f)^{\alpha_f}$$

Where:

$$\alpha_f = \alpha_0/(2(r-1))$$

$$\beta_f = \beta_0^{2(r-1)}/((r-1)A_4A_1^{2r})$$

Assumptions
1. Failure - Pre Existing Flaws
2. Flaws Grow Deterministically (Material, State, Stress Level, Stress History, Thermal History)
3. Flaws are Distribution of Residual Strength
4. Damage Rate Accumulation is of form
$\frac{\delta C}{\delta t} = M \cdot C^r$ $M \propto$ to far field work input to component
C=Critical Zone

Figure 6: Proposed Probabilistic Fatigue Model (8).

effective means of determining adhesive strength is by an examination of the vibrational characteristics of the adhesives (1). This method is useful because it allows the adhesive strength of the bond to be determined without destructively testing a panel. The adhesive is subjected to varying vibrational loads until a chemical breakdown in the material is observed. This information then allows the designer to have an idea about the maximum load that the adhesive can withstand.

Elastic stiffness as well as internal friction of the bond provide strength information. Changes in stiffness influence a number of vibrational characteristics. For instance, the nodal spacing in the flexural vibrational resonance of a panel is closely related to the flexural wave propagation velocity. Velocity of flexural waves are most sensitive to the degree of cure in the frequency range from 10kHz to 40kHz. Once information regarding adhesive strength is obtained a reliability analysis can be performed and design decisions made.

Proper design limits cannot be set without prior knowledge of the end item use. Chapter III will discuss the shelter uses and their possible design constraints.

CHAPTER III

SHELTER USES AND POSSIBLE DESIGN CONSTRAINTS

Natick Laboratories, under the direction of the United States
Army Material Command, has begun an extensive examination of current
and future field shelter requirements. It was decided that "the
mission to design and develop shelters to meet the Army's need world-
wide involves continually receiving a broad spectrum of materials,
structures, and fabrication techniques to assure that each design
incorporates the latest technology (sic)" (7). That is, the Army
is trying to use all the possible resources available through current
and future technology.

Current And Future Shelter Systems

In 1970, Natick Laboratories performed a review of all existing
shelter systems and associated industrial technologies. Along with
this, a system analysis of field shelter requirements was conducted.
The purpose of this study was ". . . to dramatically improve field
shelters and the associated technology" (7). A result of this study
was a technical plan which defined a family of field shelters to be
used in the 1985 - 1990 time frame (7).

The system analysis considered all possible approaches to
shelter design and defined technical barriers which improved tech-
nology and advancement of the state-of-the-art could overcome (7).
Output from the plan indicated those approaches which would improve

shelter characteristics most effectively. Improvement of the characteristics was necessary to meet the Army's needs yet significantly reduce the number of shelters required. General design objectives to be met by the contractor are (7):

1) Shelters should be designed so that basic shelter modules can be interchanged with one another.
2) Shelters must be designed for compatibility with transporters.
3) Shelters must be transportable.
4) Shelters must be mobile and must provide improved environmental protection.
5) Shelters must be designed to function in all climatic zones.
6) Shelters must include or allow for utilities.
7) Shelters must be reliable and maintainable.
8) Shelters must be built so as to replace existing shelters in all ranges.
9) Shelters must be designed so no special training or equipment are required.
10) Shelters must have a high strength-to-weight ratio.

The problem is to decide which materials can satisfy all, or the majority, of the aforementioned design objectives. Few structural problems should exist with the chosen material. The solution is to develop lighter materials and to carry on an intensive study of structures in terms of the loading factors involved (4).

Five types of field shelters are either now in use or planned (7). The types are pole supported shelters, frame supported shelters, air

supported shelters, rigid wall shelters and textile equipage
shelters (7).

Although pole supported and frame supported shelters are portable,
these shelters do not provide protection against the environment nor
are they suitable as maintenance facilities. Because of this the Army
is making a concentrated effort to develop air supported and rigid
wall shelters.

Single wall air supported shelters and double wall air supported
shelters are the two designs currently being investigated (7). A
shelter of the single wall construction is supported by continuous low
pressure air flow supplied by a blower located outside the shelter.
Shelters of this type offer not only excellent stability but also ease
of erection and disassembly. The only evident disadvantage is the
necessity of air locks at each opening in the shelter (7). This could
prove to be extremely costly, especially when maintenance tasks and
maintenance costs are considered. These air locks must be periodically
checked for deterioration. Should an air lock fail the entire shelter
must be removed from use to make repairs.

Double wall shelters offer the same advantages as single wall
construction, but do not require air locks (7). As can be seen in
Figure 7, the exterior and interior walls are held in position by
webs between the two surfaces that run parallel to the circumference
of the shelter. Within the walls and the webbing is an air bladder
with its own check valve. This construction allows the shelter to
remain erect for at least twenty-four hours without power, or air
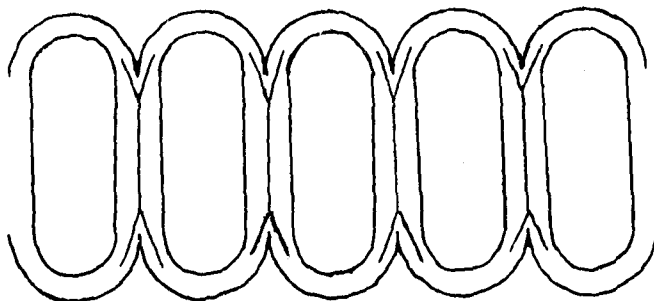
Figure 7:   Double Wall Air Supported Shelter Cell Construction.

support, even if several cells develop leaks (7). Since each cell is
separate from the other, this design enables one to neglect the pos-
sible consequences of a leak in the cell wall. In addition, the pro-
blem of providing air locks is alleviated.

Drawbacks of this system are high labor cost of fabrication,
poor quality assurance after the item is completed, and the overall
reliability of the hand fabricated joints (7). An effort is underway
to reduce the cost and improve the reliability of this system. A
manufacturing and method technology contract to utilize triple weave
or three dimensional weaves is now   t to many of the rubber
fabricators (7). This technique weaves the web to the outer and inner
walls on a special loom thus eliminating many of the joining problems.
Results of this new technique would be improved fabrication techniques

increased reliability, and lowering procurement costs by twenty
percent (7).

Rigid Wall Shelter Design
Constraints

The emphasis of this paper is a comparison of the panels used for
rigid wall shelters. The remainder of this chapter will discuss dif-
ferent shelter uses and the constraints to be considered in rigid wall
shelter design.

Rigid wall shelter is a general classification used for either
fixed (permanent) or truck transportable shelters. Prior to the
development of a family of shelters, each branch of the service con-
tracted for rigid wall shelters to meet their own needs. As time
progressed and the cost associated with each service procuring their
own shelters increased, the need for a family of rigid wall shelters
became more evident. The need was further amplified when the govern-
ment discovered that many of the shelters already in use did not con-
form to the international standards covering container sizes. This
meant additional increases in transportation cost owing to the necessi-
ty for special modes of transportation. If the shelters conform to the
American National Standards Institute or the International Standards
Organization (ANSI/ISO) set of standards, commercial containerized
shipping is an effective and economical means of transporting shelters.

The use of standard items is an essential characteristic of the
proposed shelter system. Many of the design requirements placed on
these shelters deal with this constraint. Design mandates set by the

Army for the construction of rigid wall shelters are (5):

1) Each shelter must have insulation properties to be cost effective for use with standard environmental control devices.

2) Each shelter must be capable of being erected/expanded or struck without special tools in 4 man-hours per gross 160 square feet of floor space.

3) Each shelter must be equipped with leveling devices for terrain differences up to 18 inches within the maximum dimensions of the shelter.

4) Each shelter must be compatible with standard military environmental control and power generating equipment.

5) All lighting fixtures must provide adequate lighting for medium benchwork.

6) Each shelter must have a minimum of two doors (one emergency exit) and provide an equipment access of not less than seventy-eight by seventy-two inches.

7) Each shelter must be capable of supporting a 3000 pound payload for each ten feet of length, and the gross weight of the shelter cannot exceed the 15,000 pound lift capability of the CH 47 helicopter.

8) Shelters will meet two or more of the approximate specifications shown in Table 1 depending on the feasibility of fulfilling the requirements for larger sized shelters through the combination of 8 ft. X 8 ft. X 20 ft. shelters.

Table 1: Approximate Specifications That Shelters Should
Satisfy.

Size	Floor Space (sq.ft.)	Gross Weight
8' x 8' x 6 - 2/3'	52	6500
8' x 8' x 10'	65	7000
8' x 8' x 10' exp 1 way	135	7300
8' x 8' x 20'	140	10600
8' x 8' x 20' exp 1 way	285	11200
8' x 8' x 20' exp 2 ways	435	12000
exp = expandable		

9) Maximum effort should be extended by the contractor to
standardize such items as doors, lighting fixtures, panel
sections, removable panels for environmental control
connections and any other connections.

10) Shelter walls and floors must have adequate strength to
accept fasteners capable of 2000 pounds in tension and 100
inch-pounds in torque for attachment of equipment.

Development of shelters with many of these requirements would reduce
the total cost of panels and the complexity of their maintenance tasks.
Cost of procurement would be reduced by the use of standard equipment.
Maintenance costs and maintenance tasks would be lessened since the
technicians need only understand one basic system configuration. With

rigid wall shelters' ability to provide protection from the environment, equipment lifetime could be extended.

The disadvantages inherent in the design of rigid wall shelters are the water migration properties of the core and manufacturing process control breakdowns. Any breakdown in the quality assurance inspection of these panels can lead to the eventual failure of the shelter. In fact, a breakdown in the inspection of the panels could allow production disbonds to go undetected. This might lead to the unnecessary entrapment of water within the core and premature failure of the panel. Currently, work is underway to prevent, or at least inhibit, the accumulation of water within the core.

The need for a family of rigid wall shelters, utilizing standardized items in the construction process, has developed a difference of opinion about the desirability of foam core panels or honeycomb core panels. Honeycomb core panels and foam core panels are compared against one another in Chapter IV. The comparison is made based on strength characteristics, shelter weight, electrical insulation properties, and cost.

HONEYCOMB CORE PANELS VERSUS FOAM CORE PANELS

In order to properly develop a family of rigid wall shelters, an analysis of the two panel designs is required. As was stated earlier, there is a continuing argument among many as to which configuration, foam-beam or honeycomb, provides the needed conditions in an optimum manner. This chapter will examine these two designs considering structural integrity, versatility, and lowest cost. Structural integrity is the shelter's ability to withstand the effects of storage, handling, transportation, and field use. Versatility implies that the shelter can house many types of equipment or be suited for general use. The adaptability of the shelters should not require extensive modification of the basic structure.

Shelter Strength

A series of tests were conducted by the Goodyear Aerospace Corporation on the strength characteristics of foam core panels and honeycomb core panels (6). These tests indicate that honeycomb panels can withstand larger static loads while foam panels can absorb larger shock impacts (6). Foam panels are able to attenuate shock because of the ductility of the core. This presents serious problems to the designer using honeycomb panels.

Shock is transferred from panel to panel at the interfaces between the six rigid walls. These corners are also the weakest points on the

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shelter (6). Therefore, when using honeycomb, designers must include some means of absorbing shock at each joint. This could be detrimental to the final design. Since the inclusion of any extraneous material increases shelter weight, the weight limitations on shelter design may be extended.

The ability to use one configuration in a variety of ways is an important requirement for shelters. Shelters should be useful in a number of different ways, under different loading conditions, and with different types of equipment inside. Versatility in interior utilization presents another facet to be considered.

Test results indicate that paper honeycomb core panels are more appropriate for equipment mounting (6). This is possible because of the strong, continuous orthotropic sandwich. The actual mounting of equipment is a simple process. The personnel drill a hole, fill it with epoxy, place the insert, allow it to dry, and then mount the equipment. Even if a hole were drilled through one of the honeycomb cell walls, the total strength of the core would not be significantly reduced.

Foam core panels, on the other hand, require quite a bit more. In fact, it is doubtful that any equipment mounting could be done if the panel didn't have an internal substructure. The small static load handling capabilities of foam do not permit any kind of equipment mounting (6). Here the problem arises of optimally designing a shelter so that all equipment mounts are located over the substructure hat

framing section. If the mounting fails to directly hit the sub-
structure, angle irons must be bolted to the subframe for mounting (6).
This is shown in Figure 8.
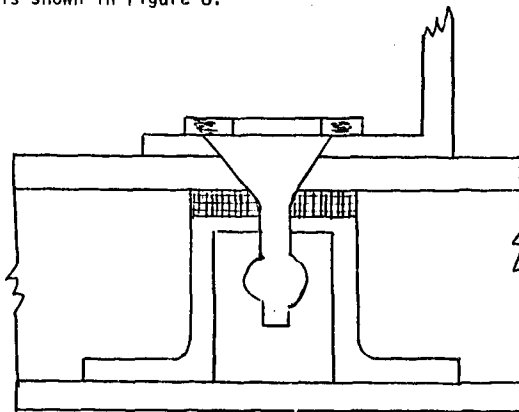
Figure 8: Equipment Mounting in Foam Panels Using Angle Irons.

Not only is this expensive, but it removes some of the space from
shelter dimensions. Since lightweight bridging members are available,
angle irons do not significantly increase the shelter weight.

Although equipment mounting is more difficult when using epoxy
held inserts, mounting is possible on foam panels if rivnuts are used.
Rivnuts are advantageous for a number of reasons (6):

1) Rivnuts located in aluminum hat sections offer significantly
   higher reliability over epoxy type installations in honeycomb.

2) Rivnuts can be installed in much less time than epoxy type
   inserts and can be loaded immediately after installation,
   whereas epoxy must set up prior to loading.

3) Higher individual insert loadings are possible using rivnuts.

In spite of the advantages of rivnuts, there is a problem in choosing a particular size shelter. The equipment insert must be placed over the metal substructure. If a considerable amount of equipment is to be installed, it may be impossible to arrange the equipment layout without choosing a larger shelter.

Tests for compressive strength also indicate that paper honeycomb is more structurally sound than foam core panels. Methods used for compressive testing entailed orienting the foam panels in two different positions and measuring the compressive strength. The honeycomb panels were tested for compressive strength without regard to panel position. Results of the tests are indicated in Table 2 (6).

Table 2: Maximum Compressive Strength Figures of Panels.

Specimen	Load at Failure
Foam*	850
Foam*	880
Foam	550
Foam	610
Honeycomb	540
Honeycomb	530
Honeycomb	540
Honeycomb	500

*Beam "U" - Down

Notice that honeycomb panels demonstrated the least amount of variation. It should also be noted that the honeycomb's average strength in

compression (520 psi) more than adequately satisfied the required
compressive strength (460 psi) (6).

Because of its strong cell walls, honeycomb proved to be the
most resistent to failure due to bending. To produce a .3 inch deflec-
tion, a three thousand pound load had to be applied to the honeycomb
panel. Whereas, to cause a similar deflection in foam panels a two
thousand pound load was necessary.

Honeycomb also proved to have the stronger shear strength (6).
Panels were tested under three conditions - dry, water-soaked, and
soaked in chemicals. The water soaked panels were submerged for forty-
eight hours, tested, submerged for 1 week, and tested again. Honeycomb,
when tested dry, withstood the maximum pressure of the testing machine
(19,600 pounds) without yielding.

Shear strength for foam-beam panels depends on the position of the
U-beam within the panel core. With the rib (U-beam) parallel to the
length of the testing machine, the maximum shear strength was eight
thousand four hundred pounds. A maximum shear strength of fifteen
hundred pounds was obtained with the rib perpendicular to the machine
orientation. Depending on whether the U-beam was facing up (U) or
facing down (∩), maximum shear strength was either twelve hundred fifty
pounds (U) or two thousand pounds (∩) (6).

After being submerged for 1 week, honeycomb shear strength was
eleven thousand six hundred pounds; three-thousand two hundred pounds
more than the strength of foam-beam panels when dry (6).

Shelter Weight

Shelter weight, as previously mentioned, is a major shelter requirement. The need for a mobile family of rigid wall shelter forces the application of the weight constraint. Nothing as concrete as the various strength tests can be employed to determine which configuration meets the design requirements while maintaining weight at a minimum.

Weight comparisons between foam and honeycomb shelters are continually performed by many of the experts. Proponents of honeycomb state they can achieve a lower density than possible with foam. The proponents of foam core want it proven (6). The only method of testing the claims is by examining each design according to a given shelter use. A foam core shelter is suitable if heavy duty is not required. The excellent thermal properties of foam is an added bonus. Honeycomb is not as advantageous for such an application because of its greater weight. This is attributable to a number of things (6):

1) Honeycomb shelters cannot meet the thermal conductivity requirement unless the open cells are filled with foam, thus adding weight to the panel.

2) The flammability and water migration properties specified by the Army cannot be approached without dipping the core in flame and water retardent chemicals. This increases the core density and adds to the shelter weight.

3) The methods used to insure the structural stability of the floor and vertical side panels under shock loads significantly increase the shelter weight.

Honeycomb manufacturers also argue that this panel design is lighter than foam panels because they eliminate the need for equipment mounting members. This argument seems valid unless one considers the epoxy inserts necessary for equipment mounting on honeycomb panels. If the number of mounting inserts is large, the weight of the honeycomb panels increases appreciably (6). Considering only panel weight, one must assume foam panels are far better than honeycomb panels.

Electromagnetic Interference And
Radio Frequency Interference

Electromagnetic interference and radio frequency interference (EMI/RFI) attenuation is a requirement which must be satisfied when the shelter houses electronic equipment. EMI/RFI shielding is usually accomplished using a gasket material specifically for that purpose. The core material has little affect on EMI/RFI shielding (6).

Extremely effective shielding can be provided for honeycomb structures. These shelters should be constructed to provide continuity of both inner and outer skins at all joints and openings. Also, since there are no through metal connections inside to outside, the integrity of the Faraday shield effect is maintained. That is, with honeycomb panels no means of through transmission of interference waves exist.

Results have indicated that a minimum attenuation of 10 db throughout a frequency range of 0.15 MHZ to 10,000 MHZ can be achieved in a bare honeycomb shelter (6). Wiring and equipping the shelters cause no loss in the attenuation factor. This is possible because all

accessories are mounted to the inner skin wall and remain isolated from the outer skin. Isolation is possible due to the poor conductive properties of the paper honeycomb cell walls.

Complete isolation of the inner walls from the outer walls is not possible with foam-beam shelters. All equipment mounting inserts must be installed in the substructure hat framing sections, which are bonded to the outer skin. Due to the inserts, the equipment is not isolated from the outer walls. This situation is depicted in Figure 9.
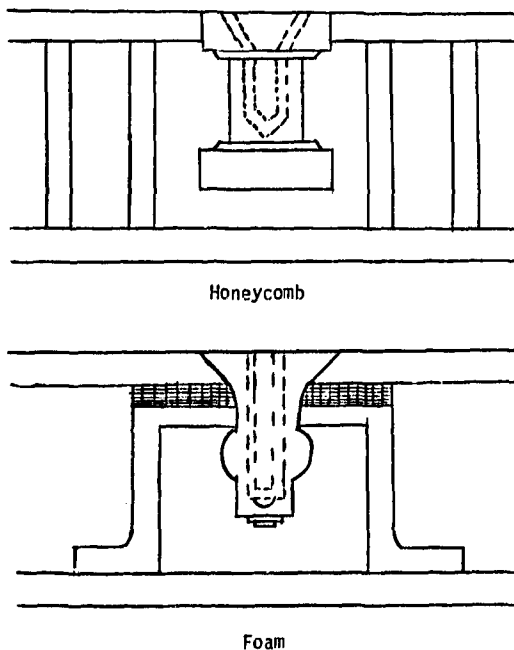

Honeycomb

Foam

Figure 9: Configuration for Equipment Mounting in Honeycomb and Foam Core Panels.

Both types of wall material offer about the same degree of EMI/RFI
shielding when only bare shelters are considered.

Panel Cost

The initial procurement cost of foam core panels is approximately
one-third the initial procurement cost of honeycomb core panels. This
is attributable to the higher material and labor cost involved in the
use of honeycomb cores. The bonding agents used in honeycomb construc-
tion are extremely expensive. Techniques used to provide the specified
insulation properties are costly, and insert installation is expensive
in terms of labor and material. Table 3, provided by the Goodyear
Aerospace Corporation, shows the difference between cost of foam panels
and honeycomb panels.

Table 3: Purchase Cost and Materials Cost of Both Foam and Honey-
comb Panels. This Table Assumes Foam Panel Cost as the Base.

Construction	Cost Per Shelter (%)		Per Unit Cost Reduction in Quantities of 8 (%)
	1 Unit	8 Units	
Honeycomb	23	35	42
Foam*	0	0	47

*Foam was used as the base figure

Keeping in mind the various uses, or desired uses, required of
the family of rigid wall shelters, the author presents his conclusions
in Chapter V.

CHAPTER V

CONCLUSIONS

The design of rigid wall shelters is complicated by requirements determined by the U. S. Army. These shelters are to be used in a variety of ways and environments. An optimal design is chosen that enables the shelters to meet these requirements. A decision is reached based on the material characteristics associated with each panel design.

From a system standpoint, field requirements appear to be better satisfied by shelters constructed of honeycomb sandwich materials. As stated in Chapter IV, honeycomb core panels have the stronger of the two designs. They show superior strength characteristics under the loading conditions of tension, compression or bending. The shear strength of foam panels does not even approach the shear strength of honeycomb panels. In fact, after being soaked in water for 1 week, honeycomb core panels still had more strength than dry foam core panels. The only weakness shown by honeycomb panels is their inferior ability to absorb shock. This presents no serious problems if some kind of shock absorbing mechanism is included in the design. Care must be exercised since the additions may cause shelter weight to exceed the desired weight. Because of their better strength characteristics, honeycomb panels are more suited for the environmental and handling extremes a family of shelters must endure.

Honeycomb core panels are more versatile than foam core panels. The ductility of foam panels causes an equipment mounting problem. In shelter design, the ideal situation is to mount the equipment without sacrificing interior space. This is often difficult. It is required that equipment mounts be installed in the panel substructure. If this is impossible, angle irons are bolted to the substructure and employed to constrain the equipment. During the design process, increased emphasis of interior utilization alleviates this problem, but raises the cost of foam panels.

Honeycomb core are inherently quite stable. Because of their soundness, these panels lend themselves well to system assembly techniques. That is, one or more walls are removed, and subsequent to equipment installation they are returned. Foam panels cannot be treated in this fashion. These shelters must be completely assembled before equipment is installed.

Even though wet honeycomb core panels are stronger than dry foam core panels, the problem of water migration still confronts the designer. Due to its cellular structures, honeycomb allows comparatively larger amounts of water to remain in the core. Water weakens the cell walls, eventually destroying the structural integrity of the honeycomb. The method currently in use to restrict water migration requires dipping the honeycomb in chemical solutions. This also makes the honeycomb more dense and heavier. Foam panels do not allow any water build-up, so this treatment is not necessary.

Foam panels were shown to be less dense than honeycomb panels. Supplementary processes were required to insure that honeycomb panels meet the flammability, thermal insulation, and water migration characteristics as prescribed by the Army. The number of epoxy bonded inserts also affects the panel weight. The presence of a large number of epoxy inserts will significantly increase panel weight. Since honeycomb shelters provide the optimum strength-to-weight ratio, the weight of these shelters is approximately the same as the weight of shelters constructed of foam core panels. This implies that the weight savings possible with foam construction is not beneficial when the shelter and not the panel is considered as the system.

Shelters constructed with honeycomb sandwich materials are also more advantageous for use as expandable shelters. Due to the stability of honeycomb structures, the actual joining of two or more shelters is not a problem. The honeycomb structure is strong enough to allow direct mounting. The honeycomb does not require the internal substructure that foam panels contain. The same arguments are used to justify this as were used for interior utilization.

Honeycomb panels appear to be more capable of meeting the needs of a mobile family of rigid wall shelters. These sandwich materials should be able to withstand any rough handling and harsh environment. The life cycle cost of each of these systems is approximately the same.

Further research could include the examination of *structurally* reinforced foam panels, and plastic *fiber* panels. These designs may prove to be more advantageous *for use with* shelters.

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